

World Water Resources at the Beginning of the Twenty-First Century

Edited by

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1 The Earth and its physical features

1.1 PHYSICAL GEOGRAPHY

1.1.1 The area of the Earth's surface

The total area of the surface of the Earth is 510 million km^2 . Over 361 million km^2 or 71% of this area is occupied by the World Ocean and only 149 million km^2 or 29% is covered by land. Water and land are distributed unevenly over the globe. In the Northern Hemisphere land extends over 100 million km^2 (39% of its area), while there are 49 million km^2 in the Southern Hemisphere (19%). The area of water in the Northern Hemisphere is 155 million km^2 (61%), and in the Southern 206 million km^2 (81%).

1.1.2 The World Ocean

The World Ocean is divided into four separate oceans by the distribution of the land (Stepanov, 1983): namely the Pacific, Atlantic, Indian and Arctic Oceans, and into numerous seas, gulfs, bays and straits. The Southern Ocean is also identified but is less well defined than the others. Basic information on the oceans and seas (Korzun, 1974b) are presented in Tables 1.1 and 1.2 respectively. The volume of water in the World Ocean is about 1340 million km³.

1.1.3 Continents and islands

During the present geological epoch the Earth's land consists of six continents: Eurasia, Africa, North America, South America, Australia and Antarctica. The borders between the separate continents are rather arbitrary. The border between Eurasia and Africa passes through the Strait of Gibraltar, along the Mediterranean Sea, Suez Canal, Red Sea, and the Straits of Bab el Mandeb. The boundary between North and South America passes through the Panama Canal. In this Monograph, Eurasia is subdivided into two parts which are considered as independent: namely Europe and Asia. The border between these continents extends from Matochkin Shar, in the north, along Pay Khoy, the Ural Mountains, Mugodzhary, along the River Emba, and the north and west coast

of the Caspian Sea and Caucasus Mountains. Information on the continents and largest islands is given in Tables 1.3 and 1.4 (Terehov, 1981).

PRIMARY WATERSHEDS

Primary and secondary watersheds can be identified on the land surface. The primary watershed divides the land into two: the first carrying runoff to the Atlantic and Arctic Oceans (60% of the land area) and the second where runoff occurs to the Pacific and Indian Oceans (40%). The secondary watersheds are those surrounding the basins of the Pacific, Atlantic, Indian and Arctic Oceans and those delineating areas of internal runoff.

The primary watershed extends northwards from Cape Horn along the Andes and the Rocky Mountains to the Bering Strait, then across the eastern plateau of Asia in a westerly direction, and then it turns to run along the eastern edge of Africa to finish at the Cape of Good Hope.

The watersheds of ocean basins are located on individual continents in the following way. In Europe the watershed between the Arctic and Atlantic Oceans passes from the southwest coast of Norway along the Scandinavian Uplands, through the Manselkya Highland, and between Segozero and Onega. The watershed line between the Atlantic Ocean and the area of internal runoff to the Caspian Sea passes between Lakes Onega and Beloye Ozero, along the Valdai Hills, through the Central Russian and the Privolzhskaya Uplands, to Ergeny and the Caucasus Mountains.

In Asia the watershed between the Atlantic and Indian Oceans extends from the south end of the Suez Canal to the source of the Euphrates River. Then the watershed between the Indian Ocean and the area of internal runoff to the north passes along the Plateau of Serkhed, through the Hindu Kush, and from the southern part of Tibet to the Kukushili Mountains to meet the Pacific Ocean watershed. The main watershed of the basins with rivers flowing into the Pacific Ocean passes from Cape Dezhnev along the Chukot, Kolyma, Dzungur, Stanovy, Yablonovy and Hentey Ranges, along the highlands of the northern area of the Gobi and further along Great Khingan Mountains, Inshan, Nan Shan, Kukushili, Tanghla, Henduanshan, to Bilau.

Table 1.1. Major hydrological and morphometric characteristics of the World Ocean

	Total area (with islands),	Area of water surface,	Area of catchment,	Water volume		Depth, m	
Ocean	$km^2 \times 10^6$	$km^2 \times 10^6$	$km^2 \times 10^6$	$km^3 \times 10^6$	%	Average	Maximum
Pacific	182.6	178.7	24.9	707.1	53.4	3957	11 034
Atlantic	92.7	91.7	50.7	330.1	24.6	3602	9219
Indian	77.0	76.2	20.9	284.6	21.0	3736	7 450
Arctic	18.5	14.7	22.5	16.7	1.0	1131	5 220
World Ocean	370.8	361.3	119.0	1338.5	100	3704	11 034

Table 1.2. Major morphometric characteristics of seas

Sea	Area, $km^2 \times 10^3$	Volume, km ³	Sea	Area, $km^2 \times 10^3$	Volume, km ³
		Pacific (Ocean		
Coral Sea	4791	11 470	Java Sea	480	22
South China Sea	3447	3 929	Sulawesi Sea	435	1586
Bering Sea	2344	3 796	Sulu Sea	348	553
Sea of Okhotsk	1617	1 317	Molucca Sea	291	554
Sea of Japan	1070	1 630	Seram Sea	187	227
East China Sea	752	263	Flores Sea	121	222
Yellow Sea	417	17	Bali Sea	119	49
Banda Sea	695	2 129	Savu Sea	105	178
		Atlantic	Ocean		
Caribbean Sea	2754	6 860	North Sea	554	52
Mediterranean Sea	2505	3 754	Baltic Sea	448	20
Gulf of Mexico	1543	2 3 3 2	Black Sea	431	555
Hudson Bay	819	92	Sea of Azov	40	0.4
Baffin Bay	689	593	Sea of Marmara	11	4.0
		Indian (Ocean		
Arabian Sea	3683	10 070	Timor Sea	615	250
Bay of Bengal	2172	5 6 1 6	Andaman Sea	602	660
Arafura Sea	1037	204	Red Sea	450	251
		Arctic (Ocean		
Barents Sea	1470	268	Kara Sea	903	101
Norway Sea	1547	2 408	Laptev Sea	678	363
Greenland Sea	1205	1 740	Chukchi Sea	590	45
East Siberian Sea	926	61	Beaufort Sea	476	478
			White Sea	91	4.4

The watershed of the rivers draining to the Arctic Ocean in Asia passes from the northern end of land in the Strait of Matochkin Shar, along the Pay Khoy Range and the Ural Mountains, to the interfluvial area of Tobol, Turgay, Ishim, and to the Kazakh area of low hills, onwards to the ranges of Tarbagatay, Mongolian Altai, Tank Ola, Hangay and Hentey, and then it extends along the watershed of rivers draining to the Pacific Ocean.

In Africa the watershed between the basins of Atlantic and Indian Oceans passes from the Gulf of Suez along the peaks of mountains situated besides the Red Sea, along the eastern part of the Abyssinian Highlands, to the east of Lake Victoria between Lake Tanganyika and Lake Nyasa, along the Muchinga Mountains, between the Rivers Congo and Zambezi, Cubango and Cunene, westwards and southwards of Lake Etosha, along

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	Area with	Area of	Altitude above sea level, m			
Continent	islands, $km^2 \times 10^6$	islands, $km^2 \times 10^6$	Average	Maximum	Minimum	
Europe	10.5	0.7	300	5642	-28	
Asia	43.5	2.7	950	8848	-392	
Africa	30.1	0.6	750	5895	-150	
North America	24.2	4.1	700	6193	-85	
South America	17.8	0.1	580	7014	-35	
Australia and Oceania	8.9	1.3	350	5029	-12	
Antarctica	14.0	0.058	2040	5140	_	

Table 1.3. Morphometric characteristics of continents

Damaraland, across the hills of the southwest and the southern borders of the Kalahari Desert, through the Drakensberg Mountains to Cape Agulhas.

In North America the watershed between the Arctic Ocean and the Pacific and Atlantic Oceans passes from Cape Prince of Wales along the Brooks Range, through the Richardson Mountains, Seluin, and Rocky Mountains, along the uplands between the Mississippi and Nelson Rivers, northwards of Lake Superior and Lake Huron and along the Labrador Peninsula. The watershed between the Atlantic and Pacific Oceans passes along the Rocky Mountains, around the upper parts of the Mississippi and South Saskatchewan, along the Isthmus of Tehuantepec and to the Panama Canal.

In South America the watershed separating runoff to the Atlantic and Pacific Oceans starts at the Panama Canal and passes along the Andes, through the Strait of Magellan along Tierra del Fuego to its southern tip.

In Australia the watershed between the basins of Pacific and Indian Oceans passes from Cape York along the Great Dividing Range to South East Point (Cape Otway).

Excluding the areas of internal runoff, the Arctic Ocean takes 15% of the runoff from the total land area of the globe, the Atlantic 34%, the Pacific 17% and the Indian Ocean 14%.

RIVERS

Depending on the size of the basin they drain, the length and volume of the flowing water, rivers are usually subdivided into very large, large, medium, small and very small. Table 1.5 presents information on the morphology of the principal river basins of the earth.

The largest river in the world is the Amazon with a catchment area of 6915 thousand km², and length 6280 km. Its total annual runoff amounts to about 15% of the total runoff of all the world's rivers. Among very large rivers are the Congo (catchment area 3680 thousand km² and length 4370 km) and Mississippi (2980 thousand km² and 4700 km). Over the world as a whole there are 20 rivers with catchment areas between 3 million

to 1 million $\rm km^2$ and 89 rivers with basin areas from 1 million $\rm km^2$ to $100\,000~\rm km^2$. Most rivers are amongst the medium, small and very small categories. About 80% of the land surface drains to the World Ocean, while the area of internal runoff where the rivers do not reach the ocean accounts for 20% of the land surface. Most of the world's largest rivers drain to the ocean

In Europe the area of internal runoff consists of the Caspian Sea basin, which includes the basins of Volga, Ural, and Kura Rivers. In Asia the area of internal runoff is larger and includes: the basin of the Aral Sea (Amu Darya, Syr Darya Rivers) the basin of Lake Balkhash (Ili River) and many rivers flowing into small lakes or disappearing in arid areas (Tedzhen, Murgab, Sary-Su, Turgay, Irgiz and Nura Rivers). There are also the deserts of Alashan, Gobi, and Takla-Makan in Central Asia, while parts of Asia Minor and most of the Arabian Peninsula have areas of internal runoff. There are several closed basins situated in the interfluvial area of the Indus and Ganges.

Almost one-third of Africa drains internally. These are the Sakhara, Libyan, Nubian, Kalahari, and Namib Deserts and semi-deserts, together with the basins of Lakes Chad, Rukwa and Turkana.

In North America the Great Basin (including Great Salt Lake), the deserts of the Mexican Plateau, the Colorado Plateau and the right bank of the Rio Grande have no outlets to the ocean, while in South America the internal runoff areas include the basins of the Lakes Titicaca—Poopo, the Puna de Atakama Desert, the semi-desert plateau of Patagonia and other territories.

In Australia Lakes Eyre, Amadeus, Torrens and Frome are closed, as well as the Great Sandy Desert, Gibson Desert and Great Victoria Desert. Little is known about drainage on the Antarctic continent

The total area of internal runoff (Korzun, 1974b) amounts to 30.2 million km², including Europe 2.2 million km², Asia 12.3 million km², Africa 9.6 million km², Australia 3.9 million km², South America 1.4 million km² and North America 0.88 million km².

Table 1.4. Principal islands of more than 10 000 km² in area

Island	Area, $km^2 \times 10^3$	Island	Area, $km^2 \times 10^3$
	KIII × 10		KIII × 10
Europe		North America	
Great Britain	230.0	Greenland	2176.0
Iceland	103.0	Baffin Island	519.0
Ireland	84.4	Victoria Island	213.8
Novaya Zemlya Islands	81.3	Ellesmere Island	202.7
Spitsbergen Islands	62.1	Cuba	105.0
Sicily	25.4	Newfoundland	111.0
Sardinia	23.8	Haiti	77.2
Franz Josef Land	16.1	Banks Island	69.9
Asia		Devon Island	56.4
Kalimantan	735.7	Southampton Island	44.1
Sumatra	435.0	Melville Island	42.1
Honshu	223.4	Alexander Archipelago	36.8
Sulawesi	223.4 179.4	Axel Heiberg Island	34.4
		Prince of Wales Island	33.3
Java	126.5	Vancouver Island	32.1
Luzon	105.6	Somerset Island	24.3
Mindanao	95.6	Aleutian Islands	17.7
Hokkaido	77.7	Prince Patrick Island	15.8
Sakhalin	76.4	The Bahamas	11.4
Sri Lanka	65.6	Jamaica	11.1
Kyushu	42.6	Queen Charlotte Islands	10.3
Novosibirsk Islands	38.4	Cape Breton	10.3
Severnaya Zemlya Islands	37.6		
Taiwan	35.9	South America	
Hainan	33.7	Tierra del Fuego	48.0
Timor	33.6	Falkland Islands	12.0
Shikoku	18.8	(Islas Malvinas)	
Seram	18.2	Australia and Oceania	
Halmahera	18.0	New Guinea	829.3
Kuril Islands	15.6	New Zealand	265.3
Sumbawa	15.5	Tasmania	68.4
Flores	15.2	Solomon Islands	40.4
Palawan	11.8	New Britain	36.6
Bangka	11.6	Fiji Islands	18.2
Sumba	11.2	Hawaii	16.2
Africa		New Caledonia	16.7
Madagascar	587.0	New Hebrides	14.8
madagascar	307.0	Bougainville Island	14.8
		Dougamvine Island	10.0
		Antarctica	
		Alexander I Land	43.2

LAKES

Lakes are widespread on all continents. There are about 15 million of them, and the total water surface area is about 2 million $\rm km^2$ or 1.5% of the land area (excluding the Antarctic). Most of the lakes are small and very small. Across the world there are 88 large lakes with a water surface area exceeding $1000 \, \rm km^2$. Of these lakes

28 are located in Asia, 13 in Europe, 16 in Africa, 22 in North America, 5 in South America and 4 in Australia. The number of lakes with a surface area greater than 10 000 km² is 19; 1 in Europe (Lake Ladoga), 4 in Asia (Aral, Baikal, Balkhash, Tonle Sap), 4 in Africa (Victoria, Nyasa, Chad, Turkana), 8 in North America (Superior, Huron, Michigan, Great Bear Lake, Great Slave Lake,

PHYSICAL GEOGRAPHY 5

Table 1.5. Major morphometric characteristics of principal world rivers

	Area of catchment.			Area of catchment,	
River	$km^2 \times 10^3$	Length, km	River	$km^2 \times 10^3$	Length, km
	4.000	Euro	=		0.00
Volga	1380	3700	Douro	95	938
Danube	817	2850	Daugava	88	1020
Dnieper	504	2200	Garonne	56	650
Don	422	1870	Ebro	87	928
North Dvina	357	1302	Tagus	81	1010
Pechora	322	1809	Seine	79	776
Neva	281	74	Mezen	78	966
Rhine	252	1320	Po	75	652
Ural	236	2534	Dniester	72	1352
Vistula	198	1092	Guadiana	72	801
Elbe	148	1165	South Bug	64	792
Loire	120	1010	Kuban	61	907
Odra	119	907	Guadalquivir	57	680
Rhône	98	812	Onega	57	416
Neman	98	937			
		Asi	ia		
Ob	2990	3650	Salween	325	2820
Yenisey	2580	3490	Godavari	313	1465
Lena	2490	4410	Huai He	270	1000
Amur	1855	2820	Krishna	259	1401
Yangtze	1808	6300	Helmand	250	1150
Ganges with	1746	5425	Yana	238	872
Brahmaputra	17.10	0.20	Liao He	229	1390
and Meghna			Olenek	219	2270
Amu Darya	1100	1415	Anadyr	191	1150
Indus	960	3180	Kura	188	1360
Mekong	795	4500	Pyasina	182	818
Huang He	752	5464	Chao Phraya	160	1200
Shatt al Arab	750	2900	Taz	150	1400
(Tigris and	750	2,00	Songka (Red)	145	1185
Euphrates)			Mahanadi	142	851
Kolyma	647	2130	Ili	140	1000
Xi Jiang	454	2214	Taimyra	124	754
Tarim	446	2000	Kerulen	120	1264
Syr Darya	440	2210	Pur	112	389
Irrawaddy	410	2300	Anabar	100	939
Khatanga	364	1634	Narmada	99	1312
Indigirka	360	1726	Narmada	"	1312
muigirka	300				
		Afri	ica		
Congo	3680	4370	Ogowe	203	850
Nile	2870	6670	Gambia	180	1200
Niger	2090	4160	Rufiji	178	1400
Zambezi	1330	2660	Cuanza	149	630
Orange	1020	1860	Ruvuma	145	800
Chari	880	1400	Qui Hon	137	830
Okowango	785	1800	Sanaga	135	860

Table 1.5. (cont.)

River	Area of catchment, $km^2 \times 10^3$	Length, km	River	Area of catchment, $km^2 \times 10^3$	Length, km
Juba	750	1600	Savi	107	680
Senegal	441	1430	Bandoma	97	780
Limpopo	440	1600	Wad Dra	95	1150
Volta	394	1600	Tana	91	720
		North	America		
Mississippi	2980	3780	Koksoak	133	1300
Mackenzie	1787	5472	Rio Grande de	125	960
Nelson	1132	2574	Santiago		
St. Lawrence	1026	3057	Brazos	118	2060
Yukon	850	2897	Mobile	116	1250
Columbia	668	1953	Colorado	110	1390
Colorado	637	2333	Mus	108	_
Rio Bravo del	570	2880	Hais	108	_
Norte			Goalzas	106	_
Churchill	298	1609	Severn	101	976
Fraser	233	1370	Fort George	98	_
Telon	142	_	Saguenay	90	_
Albany	134	975	Panuko	84	_
		South 2	America		
Amazon	6915	6280	Chubut	138	850
La Plata	3100	4700	Rio Negro	130	1000
Orinoco	1000	2740	Rio Dose	81	600
São Francisco	600	2800	Rio Colorado	65	1000
Parnaíba	325	1450	Paraíba	59	800
Magdalena	260	1530	Atrata	32	644
Essequibo	155	970	Bío Bío	24	380
		Ausi	tralia		
Murray	1072	3490	Gascoyne	79	770
Cooper Creek	285	2000	Victoria	77	570
Diamantina	115	896	Mitchell	69	520
Fitzroy	143	960	Murchison	68	700
Burdekin	131	680	Fly	64	1040
Flinders	108	930	Fortescue	55	670
Ashburton	82.0	640	Kluta	22	338
Sepik	81.0	1120			

Erie, Winnipeg, Ontario), 1 in South America (Maracaibo), and 1 in Australia (Lake Eyre).

Most lakes are situated in the Northern Hemisphere and are located in glaciated areas (there are many small lakes in the tundra). Many lakes of Europe (e.g. Ladoga and Onega) are situated in large basins, often grabens where the northern sides were eroded by ice. Tectonic depressions, glacial erosion and moraine dams form many lakes in Sweden: Vanern, Vattern, Malaren,

for example. There are many lakes formed by glacial dams in the northwest of Russia, and in Finland, Poland, Germany and Canada. A large group of lakes in the south of Finland (e.g. Lakes Saimaa and Paijanne) are divided from the Gulf of Finland by a huge dam made of a double ridge of terminal moraines, known as Salpa-Uselka. The chain of large lakes in North America (Lake Winnipeg, Lake of the Woods, and the Great Lakes: Superior, Huron, Michigan, Erie and Ontario) lie behind morainic

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deposits left by the receeding ice, which covered the whole of the north of the North America continent. A group of alpine lakes (Lake Geneva, Lake Maggiore and Lake Garda) are located in the glacially eroded basins at the foot of the Alps.

A number of lakes are located in deep tectonic depressions in mountain areas such as Baikal (1741 m), Khubsugul (267 m), Issyk Kul (702 m), Nyasa (706 m), and Titicaca (281 m). In the mountain systems of the Tien Shan, the Pamirs and the Altai there are many lakes formed from the blocking of river valleys with rock fragments during earthquakes. Among them are Lake Teletskoye in the Altai Mountains, and Lake Sarezskoye in the Pamirs in the Murghab River valley (this lake was formed in 1911 as a result of the Usoisky River being blocked).

The lakes in high mountain areas are often situated on plateaux surfaces and are mainly of a tectonic origin. Among the large lakes are Lakes Victoria (altitude 1136 m above sea level) and Tanganyika (773 m) in Africa; Titicaca (3812 m) in South America; Kara Kul (3954 m) and Chatyr Kul (3486 m) on the Pamirs, and Issyk Kul (1609 m) on the Tien Shan in Asia. One of the highest lakes is Lake Horpatso, situated in Tibet at an altitude of 5400 m.

The Caspian Sea (-27 m), and the Dead Sea (-392 m) are situated in deep depressions below sea level. The Caspian Sea and a number of other large lakes (Lakes Balkhash, Balaton etc.) are relics of former more extensive water bodies that appeared after the recession of the ice sheets.

Numerous small lakes are formed by wind action (aeolian lakes) in the hot, dry climate of the steppes such as in Western Siberia and Kazakhstan. In regions where limestone, dolomite and gypsum formations dominate the geology, there are karstic lakes, and in areas of permafrost there are thermokarstic lakes. These form when buried ice melts. Lakes of volcanic origin are frequent in Kamchatka, in the Kuril Islands, in the Armenian Highlands, in Middle and Central Asia, and in New Zealand.

Table 1.6 shows the morphological characteristics of the largest lakes. The total volume of water stored in the world's lakes is 176 400 km³; salt lakes account for 85 400 km³ and fresh lakes for 91 000 km³. The largest volume of saline waters (91% of the total volume) is found in a single water body – the Caspian Sea.

In Asia, the volume of salt lakes is only 3% of the volume of the world total; the volume of fresh waters in Asia is almost 10 times greater than the salt lakes, because of Lake Baikal which holds 27% of the total volume of the world's freshwater lakes.

In Africa all the large lakes are fresh. Lake Chad situated on the edge of the Sahara, although highly mineralized, is not related to the salt lakes. In North America among the salt lakes is the Great Salt Lake, while in South America Lake Poopo and Lake Titicaca are not salt lakes, but their water cannot be used for drinking.

RESERVOIRS

During the twentieth century the numbers of reservoirs increased markedly. They are used for public water supply, irrigation, hydropower generation and for other purposes. By the late 1980s, Avakyan *et al.* (1987) estimated there were about 30 000 reservoirs across the world with a volume of greater than 1 million m³. There were 2500 reservoirs with a capacity larger than 100 million m³, accounting for more than 90% (or 5750 km³) of both the total volume and the total surface area of all the world's reservoirs. According to the estimates available, the total volume of such reservoirs now exceeds 5750 km³, and the total surface area is about 400 000 km².

The large reservoirs constructed during the twentieth century since 1950 have substantially transformed the volume and pattern of fresh water stored on the land surface. They also allowed the development and maintenance of a large number of inter-basin transfer systems (Vugeinsky, 1991).

Of the world's reservoirs, most are valley reservoirs, which are created by damming the river channel. The biggest valley reservoir in the world in terms of volume is the Bratskoye Reservoir on the River Angara (169.3 km³), and in terms of water surface area the Volta on the Volta River (8480 km²). Since 1950, cascades of reservoirs have been constructed on many large rivers such as the Nile, Yenisei, Colorado, Euphrates, Huang He, Zambezi, Volga, Parana, Mississippi and Missouri.

Reservoirs have also been built by constructing a dam to raise the water level of an existing lake, for example, in Finland, in the northwest of the European part of Russian, and in East Africa. The largest reservoir of this type is Lake Victoria, where the dam at the Owen Falls harnesses a storage of $204.8~\rm km^3$ and a surface area of $68~800~\rm km^2$.

Along with these two types of reservoirs there are also ones filled in natural depressions by diverting water from a river or by pumping. The largest reservoir in the world of this type is Wadi-Tartar in Iraq having a volume of 72.8 km^3 and a surface area of 2000 km^2 .

Reservoirs differ widely in their usage. Hydropower reservoirs are numerous in Africa and South America. In Asia and Latin America there are reservoirs that are used primarily for irrigation.

Besides the above usage, many reservoirs on the planet are made for public water supply. In addition there are the reservoirs constructed for navigation, flood protection, fisheries, recreation, timber rafting, and for a variety of different needs. In recent decades multi-purpose reservoirs have been constructed in many parts of the world.

The greatest proportion of the world total volume of stored water is made up from the reservoirs of the USA, Russia, Canada, India and China. Information on reservoirs with a capacity of more than $20~\rm km^3$ is given in Table 1.7.

Table 1.6. Major morphometric characteristics of principal world lakes

		Maximum		G
Lake	Area, km ²	depth, m	Volume, km ³	Country
Europe				
Caspian Sea ^a	378 000	1025	78200	Russia, Kazakhstan, Azerbaijan, Iran, Turkmenistan
Ladoga	18 135	230	908	Russia
Onega	9 890	120	295	Russia
Vänern	5 648	106	153	Sweden
Chudsko-Pskovskoye	3 558	15.3	25.2	Russia, Estonia
Vättern	1 856	122	74	Sweden
Suur-Saimaa	1 800	58	36.0	Finland
Mälaren	1 140	61	14.3	Sweden
Päijänne	1116	95	18.1	Finland
Inari	1116	92	15.9	Finland
Ilmen	982	4	12	Russia
Balaton	593	12	1.9	Hungary
Geneva	584	310	88.9	Switzerland, France
Bodensee	539	252	48.5	Germany, Austria, Switzerland
Hjamaren	484	22	2.9	Sweden
Storsjon	464	74	7.38	Sweden
Asia				
Aral Sea ^{a,b}	64 100	68	1020	Kazakhstan, Uzbekista
Baikal	31 500	1741	23000	Russia
Balkhash ^a	18 200	25	106	Kazakhstan
Tonle Sap	10100^{c}	12	40	Cambodia
Issyk Kul ^a	6 280	702/668	1730	Kirghizia
Dongting Hu	6000^{d}	10	_	China
Rezaieh (Urmia) ^a	5 800	16	45	Iran
Zaisan	5 5 1 0	10	53.0	Kazakhstan
Taimyr	4 560	26	13	Russia
Koko Nor ^a	4 220	38	_	China
Khanka	4 190	11	18.5	Russia, China
Van ^a	3 760	145	_	Turkey
Lop Nor	3 500	5	(5)	China
Ubsu Nur ^a	3 350	_	_	Mongolia
Khubsugul	2 770	207	381	Mongolia
Poyang Hu	2 700	20	_	China
Alakol ^a	2 650	54	58.6	Kazakhstan
Chany ^a	2 500	10	4.3	Kazakhstan
Tuz^a	2 500	_	_	Turkey
Nam Co ^a	2 460	_	_	China
Tai Hu	2 2 1 0	_	_	China
Kara-Us-Nur	1 760	_	_	Mongolia
Tengiz ^a	1 590	8	_	Kazakhstan
Sevan	1 360	86	58.5	Armenia
Toba	1 110	529	1258	Indonesia
Marka Kul	454	27		Kazakhstan
Kara Kul	380	238	_	Kirghizia
Teletskoye	245	128	40	Russia

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Table 1.6. (cont.)

		Maximum		
Lake	Area, km ²	depth, m	Volume, km ³	Country
Africa				
Victoria	68 800	84	2750	Tanzania, Kenya, Uganda
Tanganyika	32 000	1471	17 800	Tanzania, Zaire, Zambia, Rwanda, Burundi
Nyasa	30 900	706	7 725	Malawi, Mozambique, Tanzania
Chad	$10000-25000^e$	10-11	72	Chad, Niger, Nigeria
Turkana	8 660	73	_	Kenya
Albert	5 300	58	280	Uganda, Zaire
Mweru	5 100	15	32.0	Zambia, Zaire
Bangweulu	4920^f	5	5.0	Zambia
Rukwa	4 500	_	_	Tanzania
Tana	3 150	14	28.0	Ethiopia
Kiwu	2370	496	569	Zaire, Rwanda
Edward	2 3 2 5	112	78.2	Zaire, Uganda
Leopold II	2 3 2 5	6	_	Zaire
Katnit	1 270	60	14	Nigeria
Abaya	1 160	13	8.20	Ethiopia
Shirwa	1 040	2.6	45.0	Malawi
Tumba	765	_	_	Zaire
Faguibini	620	14	3.72	Mali
Gabel-Aulia	600	12	_	Sudan
Chamo	551	13	_	Ethiopia
Upemba	530	3	0.90	Zaire
Zwoi	434	7	1.10	Ethiopia
Shalla	409	266	37	Ethiopia
North America				
Superior	84 500	406	11 600	Canada, USA
Huron	63 500	229	3 580	Canada, USA
Michigan	58 000	281	4 680	USA
Great Bear Lake	31 400	137	1 010	Canada
Great Slave Lake	28 600	156	1 070	Canada
Erie	25 800	64	545	Canada, USA
Winnipeg	24 400	19	127	Canada
Ontario	19 300	236	1710	Canada, USA
Nicaragua	8 0 3 0	70	108	Nicaragua
Athabasca	7 940	60	110	Canada
Reindeer Lake	6 640	_	_	Canada
Winnipegosis	5 3 6 0	12	16	Canada
Manitoba	4 700	28	17	Canada
Great Salt Lake ^a	4 660	14	19	USA
Lake of the Woods	4410	21	_	Canada, USA
Dubawnt	3 830	_	_	Canada
Mistassini	2 190	120	_	Canada
Managua	1 490	26	7.97	Nicaragua
Saint Clair	1 200	7	5.3	Canada
Small Slave Lake	1 190	3	_	Canada
Chapala	1 080	10	10.0	Mexico

Table 1.6. (cont.)

Maximum						
Lake	Area, km ²	depth, m	Volume, km ³	Country		
South America						
Maracaibo	13 300	35	_	Venezuela		
Titikaka	8 372	281	893	Peru, Bolivia		
Poopo ^a	2 5 3 0	3	2	Bolivia		
Buenos Aires	2 400	_	_	Argentina, Chile		
Argentino	1 400	300	_	Argentina		
Valencia	350	39	6.3	Venezuela		
Australia						
Eyre	15 000	20				
Amadeus ^a	8 000	_	_			
Torrens	5 800	_	_			
Gairdner	4 780	_	_			
Georgi	145	3	0.3			
Taupo	611	164	60	New Zealand		

^a Salt lake.

1.2 THE HYDROSPHERE

1.2.1 The origins of water on the Earth

The hydrosphere¹ surrounding the Earth includes liquid, solid and gaseous forms of water. The hydrological cycle transports this water about the Earth exchanging energy and moving materials as part of the process. The hydrosphere unity is determined by not only its continuity but also the constant water exchange between all its elements. The hydrosphere includes all types of natural waters – oceans, seas, rivers, lakes and glaciers, underground, atmospheric and biologically combined waters. The lower limit of the hydrosphere is assumed to be at the level of Mokhorovichich surface, and the upper limit practically coincides with the upper atmospheric limit (Blyutgen, 1972). Sea, lake, river, glacier, underground and atmospheric waters are all interrelated and water moves from one situation to another as the hydrological cycle progresses (Glushkov, 1929; Vernadsky, 1967).

The Earth's hydrosphere is one of the oldest mantles of this planet and it appeared between 3.5 and 4 billion years ago (Klige *et al.*, 1998). It developed together with and in close relationship to the lithosphere, the atmosphere, and then with life itself. Up to the present the mechanisms of the origin of water on the Earth have not been completely explained (Kotwicki, 1991). However, the degasification theory seems to be the most likely explana-

tion (Rubey, 1951; Vinogradov, 1959; Artyushkov, 1970; Condie, 1989). According to this theory the basic mass of the hydrosphere formed as a result of the processes of melting and degassing the Earth's mantle and it was determined by geophysical processes operating at depth.

The mechanism is assumed to be that water vapour, the carbon compounds CO₂, CO and CH, ammonia, sulphur and its compounds H₂S and SO, acid halides HCl, HF, HBr, boric acid, hydrogen, argon and some other gases came to the Earth's surface during lava degassification (Monin and Shishkov, 1979; Holland, 1989). The largest part of the volcanic gases condensed and was transformed into water, forming the hydrosphere.

Acid vapours HCl, HF, HBr, ammonia, sulphur and its compounds, and a considerable part of the CO₂ dissolved in drops of condensed water and fell as acid rain to the Earth's surface. These acid flows ran to low places (oceanic depressions) on the Earth's primary surface, at the same time reacting with underlying rocks and taking out of them the equivalent amount of alkali and alkali earths. Oceanic water appeared to be saline from the very beginning, and land waters fresh as a result of the leaching occurring in

^b Area of the Aral Sea water surface is given before reducing its level.

^c With low levels 3000 km², with high levels 30 000 km².

^d With low levels 4000 km², with high levels 12 000 km².

^e With low levels 7000–10000, with high levels 18000–25000 km².

^f With low levels 4000 km², with high levels 15 000 km².

¹ There are different interpretations of term "hydrosphere" and viewpoints on its origin (Hydrosphere, 1960; Belousov *et al.*, 1972; Chebotarev, 1978; Monin and Shishkov, 1979; L'vovich, 1986; Kotwicki, 1991; Hydrosphere, 1993a, b).

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Table 1.7. Principal reservoirs in the world with the capacity of more than 20 km^3

Reservoir	Continent	Country	Basin	Year of filling up	Dam backwater, m	Full volume, km ³	Use ^a
Owen Falls	Africa	Uganda, Kenya,	Victoria-Nile	1954	31	204.8	HFI
(Lake Victoria)		Tanzania					
Bratskoye	Asia	Russia	Angara	1967	106	169.3	HNTWFR
Nasser	Africa	Egypt	Nile	1970	95	169	IHANF
Kariba	Africa	Zambia, Zimbabwe	Zambezi	1959	100	160.3	HNIFA
Volta	Africa	Ghana	Volta	1965	70	148	HNIF
Daniel Johnson	N. America	Canada	Manicouagan	1968	214	141.8	HNS
Guri	S. America	Venezuela	Caroni	1986	162	136.3	Н
Krasnoyarskoye	Asia	Russia	Yenisey	1967	100	73.3	HNTWSFI
Wadi-Tartar	Asia	Iraq	Tigris	1976	_	72.8	SI
WAC Bennet	N. America	Canada	Peace	1967	183	70.3	HSN
Zeiskoye	Asia	Russia	Zeya	1974	98	68.4	SHNTF
Cabora Bassa	Africa	Mozambique	Zambezi	1977	127	62	HINF
La Grande 2	N. America	Canada	La Grande	1978	168	61.7	H
La Grande 3	N. America	Canada	La Grande	1981	93	60.0	H
Ust-Ilimskoye	Asia	Russia	Angara	1977	88	59.4	HNTWF
Boguchanskoye	Asia	Russia	Angara	1989	70	58.2	HNT
Kuibyshevskoye	Europe	Russia	Volga	1959	29	58.0	HNWIF
Serra Da Mesa	S. America	Brazil	Tocantins	1993	144	54.4	Н
Caniapiscau	N. America	Canada	Caniapiscau	1981	56	53.8	Н
Upper Wainganga	Asia	India	Wainganga	1987	43	50.7	
Bukhtarminskoye	Asia	Kazakhstan	Irtysh	1967	67	49.6	HFNSR
Ataturk	Asia	Turkey	Euphrare	1995	175	48.7	ΗI
Serros Coloradeso	S. America	Argentina	Neuguen	1977	35	43.4	HI
Tucurui	S. America	Brazil	Tocantins	1984	65	43.0	Н
Vilyuiskoye	Asia	Russia	Vilyui	1972	68	35.9	HWN
Sanmenxia	Asia	China	Huang He	1962	90	35.4	HISN
Kouilou	Africa	Congo	Kouilou	1992	137	35	Н
Hoover	N. America	USA	Colorado	1936	221	34.8	IHSA
Sobradinho	S. America	Brazil	São Francisco	1979	43	34.2	NHW
Glen Canyon	N. America	USA	Colorado	1966	216	33.3	HASR
Kemano	N. America	Canada	Nechako	1952	104	32.7	Н
Churchill Falls	N. America	Canada	Churchill	1971	32	32.3	Н
Nechaco	N. America	Canada	Nechaco	1953	25	32.2	H
Jenpeg	N. America	Canada	Nelson	1975	30	31.8	NH
Volgogradskoye	Europe	Russia	Volga	1961	27	31.4	HWFINTR
Keban	Asia	Turkey	Euphrates	1976	190	30.6	IH
Garrison	N. America	USA	Missouri	1956	62	30.1	SIWHA
Iroquois	N. America	USA, Canada	St. Lawrence	1958	20	30.0	HNA
Sayanskoye	Asia	Russia	Yenisey	1978	220	29.1	HINTWR
Itaipu	S. America	Brazil, Paraguay	Parana	1982	165	29.0	Н
Oahe	N. America	USA	Missouri	1962	75	28.8	HSNR
Kapchagaiskoye	Asia	Kazakhstan	Ili	1902 1970^b	41	28.1	HA
Kossou	Africa	Côte d'Ivoire	Bandama	1970	57	28.1	HIF
Rossou Razzaza Dyke	Asia	Iraq	Euphrates Euphrates	1972	15	26.0	SI
Rybinskoye	Europe	Russia	Volga	1970	18	25.4	HNTWFR
Loma de la Lata	S. America	Argentina	Voiga Neuguen	1933 1977	16 16	25.4	H H
	Asia	China	Huan He	1977	172	23.1 24.7	
Longyangxia							HIA
Mica	N. America	Canada	Columbia	1976	175	24.7	HA
Tsimlyanskoye	Europe	Russia	Don	1952	26	23.9	HFRWN

Table 1.7. (cont.)

Reservoir	Continent	Country	Basin	Year of filling up	Dam backwater, m	Full volume, km ³	Use^a
Kenney	N. America	Canada	Nechako	1952	104	23.7	Н
Khantaiskoye	Asia	Russia	Khantaika	1975	50	23.5	HN
Fort Peck	N. America	USA	Missouri	1937	76	23.0	SHIN
Xinanjiang	Asia	China	Xinanjiang	1960	100	21.6	ΗА
Ilia Solteira	S. America	Brazil	Parana	1974	85	21.2	HN
Yacyreta	S. America	Argentina, Paraguay	Parana	1991	41	21.0	HNI
Furnas	S. America	Brazil	Grande	1965	96	20.9	ΗA
E1 Chocon	S. America	Argentina	Limay	1975	65	20.2	HIA

^a H, hydropower; N, navigation; W, water supply; I, irrigation; F, fishery; T, timber rafting; R, recreation; A, accumulation; S, struggle with inundations.

the upper zone of the Earth's crust, remaining saline only in deep areas.

Some scientists (Shoemaker, 1984; Alvarez, 1987) do not agree with this theory on the origins of the hydrosphere. They consider that the Earth has experienced during its history numerous collisions with comets that were potential sources of water.

Estimates of the amount of water formed in this way at early stages of the evolution of the Earth vary from 4% to 40% (Chyba, 1987) and some suggest even higher proportions (Hoyle, 1978) of the volume.

Present-day geological studies have shown that the hydrosphere existed during most geological periods (Markov, 1960; Strakhov, 1963). According to calculations (Timofeyev *et al.*, 1988) the Earth's mantle contains 28×10^9 km³ of water, which supports degasification as the origin of the hydrosphere.

During the early history of the Earth degasification was more intensive. The basic mass of the hydrosphere would probably have formed during the first hundreds of millions of years. Oceans appeared rapidly during this time (Kuenen, 1950).

However, Revelle (1955) was of the opinion that the oceans appeared late and quickly. According to Schopf (1980), the major volume of degasification occurred between 4.6 and 2.5 billion years ago, and according to Sorokhtin (1974), the maximum rate of growth took place during the Lower Riphean.

New studies (Staudacher and Allegre, 1982; Hydrosphere, 1993a, b) show that the Earth degasified rapidly during the 50 million years after it originated. The results of further studies in this area have been generalized by Holland (1989) and Kump (1989).

During the Archean Period the Earth's surface relief was subdued and water covered an area of about 500 million km² (Klige, 1992). There was a warm and humid climate without distinct latitudinal zones and with alternating periods when minor warming and cooling occurred together with glaciation (Monin and Shishkov, 1979). In the Proterozoic Era, photosynthesis became active with

the development of live matter in the hydrosphere (Alpatjyev, 1983).

The gradual increase in the land area with the growth of the thickness of the Earth's crust and the development of mountains exerted a considerable effect on the hydrological cycle. At this time conditions were more arid and ice sheets developed in distinct climatic zones, the hydrological cycle between the oceans, atmosphere and land grew more active and a river network developed (Drozdov *et al.*, 1981).

In the Palaeozoic Era the hydrological cycle became more complicated due to changes in the ratio between the area of ocean and land. During this period the ocean reached its greatest size in the Ordovician. Marine deposits show that this was the most powerful transgression in the history of the Earth. The land area was 72 million km² or 50% of its present size. The sea level rose by more than 250 m and 83% of our planet was covered by water (Klige, 1980). In contrast, the area of the land was greatest during the Mesozoic when the sea level was 100 m lower than at present.

Simultaneously with the decrease in the size of the ocean and an increase in the elevation of the continents, as a result of the development of mountain-forming processes, climatic conditions became more arid, runoff decreased, and a considerable part of the water became locked up in ice sheets and glaciers. At this time the character of the water cycle came close to the one that exists today. By the Mesozoic the gaseous composition of the atmosphere had changed greatly, as a result of the increase in the amount of carbon dioxide and oxygen due to the development vegetation and animal life. There is evidence of boreal, humid and subtropical climates on land in the late Triassic (Razumikhin, 1976).

The recent great oceanic transgression started at the end of the Jurassic Period and reached its maximum in the Cretaceous Period. Since then the ocean has, in general, regressed and the land area has increased (by about 35 million km²), and this has been accompanied by powerful mountain-building of the Alpine

 $^{^{\}it b}$ In 1970 the filling of the reservoir was stopped. The project reservoir capacity was not attained.

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Table 1.8. Water content in the hydrosphere

Type of water	Area of distribution, $km^2\times 10^3$	Volume, $km^3 \times 10^3$	Water layer, m	Fraction of total volume of hydrosphere, %	Fraction of fresh water, %
World Ocean	361 300	1 338 000	3700	96.5	_
Ground water (gravity and capillary)	134 800	23400^a	174	1.7	
Predominantly fresh ground water	134 800	10 530	78	0.76	30.1
Soil moisture	82 000	16.5	0.2	0.001	0.05
Glaciers and permanent snow cover:	16 227.5	24 064	1463	1.74	68.7
Antarctica	13 980	21 600	1546	1.56	61.7
Greenland	1 802.4	2 340	1298	0.17	6.68
Arctic Islands	226.1	83.5	369	0.006	0.24
Mountainous regions	224	40.6	181	0.003	0.12
Ground ice of permafrost zone	21 000	300	14	0.022	0.86
Water in lakes:	2 058.7	176.4	85.7	0.013	_
Fresh	1 236.4	91.0	73.6	0.007	0.26
Salt	822.3	85.4	103.8	0.006	_
Swamp water	2 682.6	11.5	4.28	0.0008	0.03
River stream water	148 800	2.12	0.014	0.0002	0.006
Biological water	510 000	1.12	0.002	0.0001	0.003
Water in the air	510 000	12.9	0.025	0.001	0.04
Total volume of the hydrosphere	510 000	1 386 000	2718	100	_
Fresh water	148 800	35 029.2	235	2.53	100

^a With no account of underground water of the Antarctic, approximately estimated at 2 million km³, including predominantly fresh water of about 1 million km³.

type on most continents. This has lead to an increasing in the role for continental water in the global water cycle.

More recently, wide fluctuations in the distribution of land and water can be traced particularly in the Pleistocene, over the last million years as a result of the change in climatic conditions accompanied by alterations to the water regime on the Earth's surface. Cooling, which appeared periodically as a result of variations in the amount of solar radiation coming to the Earth's surface, led to the formation of large continental glaciations. Glaciers accumulated huge masses of water – more than 60 million km³, which resulted in the lowering of the sea level by more than 100 m. At the same time a considerable amount of moisture (up to 1 million km³) was accumulated in the extensive closed drainage basins on the continents. There are also changes in the volume of ground water with storage increasing considerably during the humid periods.

1.2.2 The contemporary hydrosphere

There are no large disagreements in the estimates of the volume of the present hydrosphere (Korzun, 1974a; Kotwicki, 1991; Hydrosphere, 1993a, b), since it is determined, basically, by the enormous volume of water contained in the World Ocean. The

volume of the hydrosphere is most frequently estimated to be 1370 million km³ and this figure is practically equal to the water volume in the World Ocean. However, as more information becomes available about the relief of the ocean bottom, particularly for the Arctic Ocean, where underwater ridges have been discovered, there have been reductions to a total of 1338 million km³, i.e. a reduction of 32 million km³ (Frolov, 1971). The total volume of the hydrosphere, according to current data (Korzun, 1974) is 1386 million km³ (Table 1.8). Fresh water in all its states makes up only 2.53% of the total, of which 1.74% is in the ice sheets of the Antarctic and the Arctic and in mountain glaciers.

In addition to free (gravitational) water, the lithosphere contains a large amount of physically and chemically combined water. The average content of the physically and chemically combined waters amounts to 3.5% of the rock weight, i.e. some 0.84×10^{24} g (Derpgolts, 1971). Combined water does not participate actively in the hydrological cycle, at least at recognizable time-scales, and is not taken into account in this present study.

THE WORLD OCEAN

Table 1.8 shows that the World Ocean holds by far the largest part of total volume of water on the planet. However, in recent

Table 1.9. Present-day glaciation of continents and islands of the Earth

Region	Area of glaciers, km ²	Water volume, km ³
Arctic		
Greenland	1 802 400	2 340 000
Franz Josef Land	13 735	2530
Novaya Zemlya	24 420	9 200
Severnaya Zemlya	17 470	4 620
Arctic Islands	226 090	83 500
Canadian Archipelago	148 825	48 400
Spitzbergen (Western)	21 240	18 690
Small Islands	400	60
Total	2 028 490	2 423 500
	2 020 190	2 123 300
<i>Europe</i> Iceland	11785	3 000
Scandinavia	5 000	645
	3 200	350
Alpes Caucasus		95
	1 430	
Total	21 415	4 090
Asia		
Pamir-Altai	11 255	1 725
Tien Shan	7 115	735
Dzungarian Ala Tau, Sayan Mountains	1 635	140
Eastern Siberia	400	30
Kamchatka, Plateau of Koryak	1510	80
Hindu Kush	6 200	930
Karakoram Pass	15 670	2 180
Himalayas	33 150	4 990
Tibet	32 150	4 820
Total	109 085	15 630
North America		
Alaska (Pacific Coast)	52 000	12 200
Inner Alaska	15 000	1 800
USA	510	60
Mexico	12	2
Total	67 522	14 062
South America	2,2	
Venezuela, Colombia, Andes, Tierra del Fuego	7 100	2 700
Patagonian Andes	17 900	4 050
Total	25 000	6750
	25 000	0750
Oceania N 711	1,000	100
New Zealand	1 000	100
New Guinea	14.5	7
Total	1 014.5	107
Africa		
Kenya, Mount Kilimanjaro, Ruwenzori	22.5	3
Antarctica	13 980 000	21 600 000

years, studies have appeared (Sofer and Skirstymonskaya, 1994; Wallace, 1996) that show volumes which differ from the data here by between 0.7% and 10%. Including the water stored in the bottom silts of the oceans causes the 10% difference.

The World Ocean has accumulated 3.06×10^{25} Joules of heat (Stepanov, 1983). Every year it takes up almost twice as much solar energy as the land, and this factor determines its important role in the planetary heat exchange. The major portion of this energy is employed in evaporating over 500 000 km³ per year of water, which ensures global water exchange.

GLACIERS AND ICE SHEETS

The largest volume of fresh water is stored in the planet's glaciers and ice sheets. The total area of the present glaciation exceeds 16.2 million km² (Kotlyakov, 1997). The mean ice thickness on this area is 1700 m, and the maximum is more than 4000 m (in Antarctica). The distribution of ice sheets and glaciers and the water stored in them is given in Table 1.9. The data on glacier thickness and water storage are approximate. To estimate the mean thickness of ice data were used from the few measurements from ice drilling and seismic sounding (Korzun, 1974b). These data were applied by analogy to other glaciers taking into account their morphological features. The accuracy of the assessment of that water storage in the Antarctica, for example, is about ± 3.0 million km³. The total water volume in the ice across the globe is estimated to exceed 24 million km³ (Korzun, 1974b). Most of the water stored in the ice cover is concentrated in Antarctica (almost 90%), while the remainder is found in Greenland (almost 10%) and in mountain glaciers.

Glaciers are giant "water reservoirs" and "coolers" greatly influencing the climate and water regime of the Earth (Kotlyakov, 1979). Their state and the changes from this state over time are an important indicators of global climatic and hydrological changes – past, present and future. Cooling and warming and the advance and recession of glaciers result in the change of all the elements of the hydrological cycle: precipitation, runoff and evaporation, and the volume of water stored on land and in the ocean. During glaciation a large amount of water becomes locked up as snow and ice on the land. As a result the volume of runoff decreases, the World Ocean level falls by tens of metres, uncovering extensive areas of the continental shelves. With the decline of glaciation, river flow increases, the volume of water in the ocean becomes larger, the level rises and the land area diminishes.

UNDERGROUND ICE

Areas of permafrost extend over northeast Europe and the north and northeastern parts of Asia, including the Arctic islands; they cover northern Canada and the fringes of Greenland and THE HYDROSPHERE 15

Antarctica, as well as higher parts of South America. The total area of permafrost is about 21 million km², some 14% of the land area. In the Southern Hemisphere (Antarctica, South America) permafrost covers about 1 million km². The depth of permafrost ranges from 400 to 650 m. Underground ice within this range is found as vein formations and strata. The water stored as underground ice can be estimated only approximately due to lack of data and few studies (Grave, 1968) but the most likely figure is 300 thousand km³ (Korzun, 1974b). In the permafrost areas 150–200 km³ of water occurs in the form of river ice.

The annual snowfall over the Earth is about 1.7×10^{13} tonnes, and this snow covers an area of between 100 and 126 million km². The distribution of snow varies considerably from year to year depending on climatic conditions.

UNDERGROUND WATER

The volume of gravitational water contained in the pores, fissures and fractures of the water-saturated strata of the Earth's crust represents the natural storage of water underground. The geographical distribution of ground water is closely related to the geological structure of the Earth's crust. It also depends considerably on the climatic factors: precipitation, condensation and evaporation, and particularly on the infiltration. Since runoff also depends on these factors, there is a strong relationship between ground water and runoff: ground water draining to rivers are included in the volume of runoff, being its most stable contribution to the hydrograph, especially during dry periods and drought.

The reliable estimation of ground water storage is very difficult (Garmonov *et al.*, 1974). The water content of water-bearing strata can be obtained approximately by multiplying the volume of water-bearing table by a water loss factor and effective porosity. The natural storage of ground water is determined down to the absolute depth of 2000 m – the depth of the isobath which indicates approximately the distribution of the Earth's continental crust.

Three zones of ground water movement can be distinguished vertically:

- A zone of active water exchange is located above the local base level and is highly dynamic. Movement of water in this zone increases with height above the base level. Here the character of the water is most closely related to the nature of the overlying soil and to the rock strata containing them and also to climatic factors. The effective porosity of this zone is about 15%.
- 2. A zone of less active water exchange is located below this first zone down to sea level. This zone is situated below local base levels and the water here is only affected by large rivers which may have deep channels. Drainage of ground water in this zone is also related to basins and depressions.

Table 1.10. Natural ground water resources in the upper layer of the Earth's crust by hydrodynamic zones

Continent	Zone ^a	Ground water resources, $km^3 \times 10^6$	Total resources of ground water, $km^3 \times 10^6$
Europe	1	0.2	1.6
	2	0.3	
	3	1.1	
Asia	1	1.3	7.8
	2	2.1	
	3	4.4	
Africa	1	1.0	5.5
	2	1.5	
	3	3.0	
North America	1	0.7	4.3
	2	1.2	
	3	2.4	
South America	1	0.3	3.0
	2	0.9	
	3	1.8	
Australia and	1	0.1	1.2
Oceania	2	0.2	
	3	0.9	

^a For explanation of zones see text.

Where these lie under the sea the discharge of water from this zone occurs into the sea. Less movement provides for higher mineralization of ground waters, however here they are basically fresh or weakly mineralized. The nature of the waters in this zone is determined by the occurrence of aquifers and aquicludes and their juxtaposition in the form of depressions, troughs, synclines and monoclines forming artesian basins. The effective porosity of this zone is 12%.

3. A third zone lies in the crust from sea level to the absolute depth – 2000 m. The waters of the upper part of this zone are only influenced by the biggest rivers at depth, and by large-scale features such as depressions in the relief of land and the ocean. In the upper part of this zone water is fresh or weakly mineralized, with saline water and brines below. The effective porosity is 5%.

The mean altitude of each continent was used for calculating the total volume of ground water stored in the Earth's crust (Korzun, 1974b). The total storage of ground water to the 2000 m level in the Earth's crust was estimated to be 23.4 million km³ (Table 1.10). With 3.6 million km³ in the first zone, 6.2 million km³ in the second and 13.6 million km³ in the third, rivers are fed mainly from water stored in the first zone.

Table 1.11. Water resources in the principal lakes of the Earth

	Number	Total area,	Water res	Water resources, km ³		
Continent	of lakes	$km^2 \times 10^3$	Fresh	Salt		
Europe	34	430.4	2 027	78 000		
Asia	43	209.9	27 782	3 165		
Africa	21	196.8	30 000	_		
North America	30	392.9	25 623	19		
South America	6	27.8	913	2		
Australia and Oceania	11	41.7	154	174		
Total	145	1300	86 500	81 360		

Table 1.12. Area of bog over the Earth

Continent	Bog area, $km^2 \times 10^3$
Eurasia	925
Africa	341
North America	180
South America	1232
Australia and Oceania	4

Table 1.13. Water volume in river channels of the Earth

Continent	Water volume in river channels, km
Europe	80
Asia	565
Africa	195
North America	250
South America	1000
Australia and Oceania	25

LAKES AND RESERVOIRS

There are 145 large lakes across the globe with an area of 100 km² and holding 168 thousand km³ of water (Korzun, 1974b) (Table 1.11). This is 95% of the total volume of all the world's lakes, giving a total volume of lake water of 176.4 thousand km³. Of this total 91 thousand km³ is fresh water, and 85.4 thousand km³ is salt. The hydrology of about 40% of the world's large lakes has not been studied and their volumes are estimated approximately.

Some studies (L'vovich, 1986; Wallace, 1996) exaggerated estimates of the water stored in lakes and these vary from $200\,000\,\mathrm{km^3}$ to $278\,000\,\mathrm{km^3}$. The hydrosphere includes water held in reservoirs. Their total volume exceeds $6000\,\mathrm{km^3}$ and they regulate about 15% of the Earth's total runoff.

WATER STORED IN SWAMPS, CHANNEL NETWORKS, SOIL, LIVING ORGANISMS, PLANTS AND THE ATMOSPHERE

Swamps and bogs are widespread across the Earth with a total area of approximately 2.7 million km² or about 2% of the land area. The most swampy continent is South America (Table 1.12). The total volume of water in the world's swamps and bogs is estimated to be about 11 470 km³ (Korzun, 1974b). This value has been obtained on the assumption that the mean thickness of the peat bogs is 4.5 m, their volume is 12 070 km³, and that they are 95% water.

The hydrosphere also includes the water stored in the river channel network. The total volume of this water – 2120 km³ – was estimated by the State Hydrological Institute (Korzun, 1974b) taking into account the volume of runoff and the lengths of the main rivers and their tributaries (Table 1.13). According to L'vovich (1986) this volume is 1200 km³. In spite of the very small volume of water in the river channels, it is this water which is continuously renewed and which is most important for human use.

The soil moisture is an integral part of the hydrosphere. This water occurs mainly in the top 2 metres of the soil. The total volume of soil moisture is estimated to be approximately 16 500 km³ (Korzun, 1974b). This figure assumes that soil moisture is 10% of the 2-m layer, and that the area of soil containing moisture covers 55% of the land area or 82 million km². L'vovich (1986) estimated the total volume of soil moisture to be 83 thousand km³; however he did not state the method used to estimate it.

Biological water (the water included in living organisms such as plants and animals) is an active link in the hydrologic cycle. Part of the water that evaporates from the land and enters into the atmosphere is due to transpiration of soil moisture by vegetation. Alpatjyev (1969) gives the volume of living matter in the biosphere as 1.4×10^{12} tonnes. The water content of living matter is about 80% (Derpgolts, 1971), i.e. 1.12×10^{12} tonnes or approximately 1120 km³

The water contained in the atmosphere, as water vapour, water drops and ice crystals, is an important part in the hydrosphere, possibly the most active part. The total volume of moisture in the atmosphere, according to the different estimates (Korzun, 1974b; L'vovich, 1986; Wallace, 1996), varies from 12 900 km³ to 14 000 km³.

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1.2.3 Global water exchange in the hydrosphere – the hydrological cycle

The waters of the hydrosphere are in constant, usually cyclic, motion under the effects of solar radiation, the energy released from the Earth's interior and gravitational forces. Due to geological processes about 1 km³ of water a year is released from the mantle through degasification and this rises gradually to the Earth's surface. As a result of convection in the mantle, part of this matter can emerge through breaks in ocean rift zones related to oceanic ridges (Monin, 1977). The global process of water exchange provides some stability in the distribution of waters between the land, the oceans and the atmosphere. This equilibrium is relative and can change in time, and these changes can lead to corresponding changes in hydrological and climatic conditions.

Water evaporating from the surface of reservoirs, soil and vegetation enters into the atmosphere as water vapour where it is dissipated upwards by turbulent diffusion and is transported by air currents from one place to another. With a temperature decrease, water vapour is condensed, transforming it to a liquid or solid. During rainfall from clouds, part of the water returns to the Earth's surface (inland cycle), and part of it returns to reservoirs in the form of runoff. Some precipitation can fall into the ocean.

Water evaporated from the surface of the oceans and seas mostly (90%) falls back into the sea, short-circuiting the cycle. A smaller part of it (10%) participates in the major cycle, being transported by atmospheric circulation to the land where, as rainfall, it can be involved in a number of smaller versions of the complete hydrological cycle when surface and ground water and ice drainage reaches the World Ocean, closing the complete cycle. Part of the water is combined and decomposed by plants.

Part of the water contained by the Earth is in chemical compounds, such as crystal hydrate, sorbate and many other forms which are found in porous deposits in the Earth's crust. This chemically combined water can be removed from the total water exchange for thousands of years. The crustal rocks lose water during the process of metamorphization and subduction under the effects of high pressure and high temperature. This water rises through rock pores and appears on the Earth's surface (Vinogradov, 1973).

The global hydrological cycle is not a closed system. Solar energy and energy from space, together with cosmic dust, meteorites and meteors, arrive from space. The Earth in its turn gives back part of its energy to space and dissipates hydrogen and helium to it (Alpatjyev, 1983; Kulp, 1951). This exchange of matter and energy brings about 0.01 km³ of water per year (Derpgolts, 1971; Alpatjyev, 1969) from space to the Earth. At the same time part of the hydrosphere is lost due to the dissipation of light gases, and their escape beyond the limits of the Earth's gravitational field,

Table 1.14. Periods of renewal of water resources on the Earth

Water of hydrosphere	Period of renewa
World Ocean	2 500 years
Ground water	1 400 years
Polar ice	9 700 years
Mountain glaciers	1 600 years
Ground ice of the permafrost zone	10 000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 year
Channel networks	16 days
Atmospheric moisture	8 days
Biological water	several hours

amounting to about 0.1 km³ per year (from 0.03 to 0.27 km³: Yuri, 1959; Pavlov, 1977; Alpatjyev, 1983).

Every year human influences grow and cause more and more changes to natural processes, including the hydrological cycle. These changes bring about alterations to the water balance and to water resources and their availability. The rapid growth of population, the development of industrial production and the rise of agriculture have resulted in the increased use of water, reaching a global total of about 4 thousand km³ per year (Shiklomanov, 1997) by 1990. Some 80% of this water is used for agriculture, primarily for irrigation, and this causes more evaporation and an intensification of the hydrological cycle.

Human activities have also changed the character of ground water. Although there are some examples of artificial recharge of aquifers, more often the water table has been lowered to provide water for drinking. Every year up to 20 thousand km³ of ground water is abstracted (Plotnikov, 1976), which results generally in the reduction of aquifer storage and the lowering of ground water levels, and in some cases in land subsidence.

The construction of reservoirs has led to the slowing down of the movement of river waters (Kalinin, 1974). Slowing the movement of water can influence its quality particularly by the accumulation of pollutants. Because the World Ocean water is contaminated by oil products, this leads to the reduction of evaporation from the water surface by about 10% (Duvanin, 1981) and this contributes to the reduction in the rate of exchange of water between the ocean and the land surface.

Of course water in the hydrosphere is connected by the hydrological cycle; however the rates of movement and residence times are very different for water in its different states (Table 1.14). Table 1.14 shows that biological waters included in plants and living organisms are renewed most rapidly – perhaps over a period

of a few hours. Plants transpire this water. Atmospheric water, which forms due to evaporation from any water surface, is renewed on average over 8 days. Water stored in the channel network is also renewed on average over a period of 16 days. The soil water is renewed over a period of a year and is spent mainly for evaporation and partly on runoff. Water stored in swamps has a 5-year residence time.

Most lake water is renewed on average over a period of 17 years. However different lakes have different renewal times. For example, for Lake Baikal this time is 380 years. All other types of natural waters (glaciers, ground waters, ocean waters etc.) are renewed more slowly, possibly over periods of thousands and even tens of thousands of years. The largest period is for the ice in the tundra and in Antarctica, which may be renewed only over several hundreds of thousands of years (Kotlyakov, 1984).

The time data presented here for the exchange of natural water in the global hydrological cycle (Korzun, 1974b; L'vovich, 1986) are very approximate and typical of the lower limits of the exchange process (Kalinin, 1972).